

A DIP AFTER THE EARLY EMISSION OF SUPER-LUMINOUS SUPERNOVAE: A SIGNATURE OF SHOCK BREAKOUT WITHIN DENSE CIRCUMSTELLAR MEDIA

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ABSTRACT

The origin of super-luminous supernovae (SLSNe), especially the source of their huge luminosities, has not been clarified yet. While a strong interaction between SN ejecta and dense circumstellar media (CSM) is a leading scenario, alternative models have been proposed. In this *Letter*, we suggest new diagnostics to discriminate the strong SN-CSM interaction scenario from the others: a decline in the luminosity ('dip') before the main peak of the light curve. This dip is an unavoidable consequence of having a dense CSM within which the shock breakout occurs. If a dense CSM shell is located far at large radii from the progenitor inside, it takes time for the SN ejecta to reach it and the early light curve can be powered by the SN ejecta before the collision. Once the SN ejecta collides with the dense CSM, the electron density and thus the Thomson scattering opacity suddenly increase. Photons become unable to go out of the shock even if there is a source of emission inside, which results in the dip in the light curve. This dip is a solid prediction from the strong interaction scenario irrespective of a power source for the early emission. Eventually the forward shock breaks out from within the dense CSM, and the luminosity increases by the continuous strong SN-CSM interaction, resulting in an SLSN. The possible dip observed in the hydrogen-poor SLSN, 2006oz, could be the first example of this signature and give support to the SN-CSM interaction as the power source of SLSN 2006oz.

Subject headings: supernovae: general — supernovae: individual (SN 2006oz)

1. INTRODUCTION

The origin of the huge luminosities of super-luminous supernovae (SLSNe), categorized by maximum luminosities exceeding $\sim 10^{44}$ erg s⁻¹, is one of the biggest mysteries in the study of stellar explosions. SLSNe are roughly divided into two groups based on the existence or non-existence of hydrogen lines in their spectra (H-rich and H-poor SLSNe). The origin of H-rich SLSNe is most likely a strong interaction between the SN ejecta and a dense circumstellar medium (CSM) (e.g., Woosley et al. 2007; Chevalier & Irwin 2011; Moriya & Tominaga 2012; Svirski et al. 2012; Moriya et al. 2012) because many such events show narrow H emission lines (i.e., they are Type IIn SNe) which indicates the existence of a dense CSM (e.g., Smith et al. 2010). On the other hand, the origin of H-poor SLSNe is not yet well-understood. Some of them show light curves (LCs) whose decline rates after the peak are consistent with the ⁵⁶Co decay and they are likely powered by a large amount of ⁵⁶Ni (e.g., Gal-Yam et al. 2009; Young et al. 2010; Moriya et al. 2010). However, this is not the case for the majority of H-poor SLSNe. Their LCs generally decline much faster than the ⁵⁶Co decay (Quimby et al. 2007, 2011; Barbary et al. 2009; Pastorello et al. 2010; Chomiuk et al. 2011). For these H-poor SLSNe, several mechanisms to power the LCs have been suggested, including an interaction of SN ejecta with C+O-rich dense

CSM (e.g., Blinnikov & Sorokina 2010), a spin-down of a highly-magnetized neutron star (e.g., Kasen & Bildsten 2010; Woosley 2010; Maeda et al. 2007), or a quark nova model (e.g., Ouyed & Leahy 2012). However, there has been no clear observational evidence to distinguish the actual heating mechanism of H-poor SLSNe.

Recent observations of an H-poor SLSN 2006oz revealed the existence of the early emission before the main part of the LC (Leloudas et al. 2012). The early emission was observed to continue about 10 days at the bolometric luminosity of $\sim 10^{43}$ erg s⁻¹, followed by a possible decline in the luminosity for a few days (a 'dip'). Then the luminosity increased to at least $\sim 10^{44}$ erg s⁻¹ in the timescale of $\simeq 30$ days ('main LC'). It is unlikely that emission from SN 2006oz was powered by the ⁵⁶Ni decay, since most of the ejecta ($\simeq 10 M_{\odot}$) would have to be ⁵⁶Ni to simultaneously explain the rising time and the peak luminosity of SN 2006oz with ⁵⁶Ni heating (Leloudas et al. 2012). The origins of the early emission and the possible dip in the LC have not yet been clarified (Leloudas et al. 2012).

In this *Letter*, we explore a consequence of the SN-dense CSM interaction scenario for SLSNe. We show that this scenario predicts that the luminosity of SLSNe should decline for a while before the strong interaction that powers the huge luminosity begins. The dip is an inevitable consequence of the shock breakout within the dense CSM (Chevalier & Irwin 2011; Moriya & Tominaga 2012; Svirski et al. 2012, see also Ofek et al. 2010; Balberg & Loeb 2011). The possible dip observed in SN 2006oz could be the first example of this and it indicates that the SN-CSM interaction is the power source of the H-poor SLSN 2006oz.

2. DENSE CIRCUMSTELLAR MEDIUM AROUND SN 2006OZ

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We explore a consequence of the SN-dense CSM interaction scenario to power the emission from SLSNe. Although our arguments apply to any SLSNe powered by interaction, we focus on SN 2006oz to provide our basic idea. This SLSN is the best example so far for which the early phase behavior has been well observed. First, we estimate physical properties of the dense CSM around the progenitor of SN 2006oz, under the assumption that the main LC was powered by the interaction between SN ejecta and dense CSM. Then, with these constraints, we discuss what is expected to take place in the proposed system before the main LC.

Figure 1a presents the progenitor system required in the strong interaction scenario. A dense CSM shell exists between R_i and R_o . Once the SN ejecta reaches R_i , the strong interaction takes place until the ejecta reaches R_o , and this interaction powers the main LC. An early emission is created in the phase before the ejecta reaches to R_i . Our main arguments below do not depend on the nature of a power source for the early emission, and thus we proceed without specifying it (see Section 4 for possible origins for the early emission). The CSM should be dense enough to explain the peak luminosity of SN 2006oz by the interaction scenario, and the shock breakout is expected to take place within the CSM at the beginning of the strong interaction. The radius where the shock breakout occurs is expressed as xR_o (where $R_i/R_o < x < 1$). As we focus on H-poor SLSNe, we assume that the CSM is mainly composed of C and O, and the progenitor star is a Wolf-Rayet (WR) star. In the following, we assume that the dense CSM is uniformly distributed with a constant density. This is just for the sake of simplicity, and the main result is not sensitive to this assumption. Under these assumptions, we estimate properties of the dense CSM by comparing the shock breakout prediction and the observed features of SN 2006oz.

The blackbody radius obtained from the spectrum near the main LC peak of SN 2006oz is about 2.5×10^{15} cm (Leloudas et al. 2012). Since the last scattering surface of the CSM at the main LC peak is expected to be at the outermost region of the dense CSM shell when the density is constant in the dense CSM (Moriya & Tominaga 2012), we can estimate that $R_o \simeq 2.5 \times 10^{15}$ cm. On the other hand, the blackbody radius at the beginning of the main LC rising phase (i.e., at the beginning of the strong interaction just after the shock breakout within the CSM) is $\simeq 10^{15}$ cm (Leloudas et al. 2012). Thus, we can estimate that $xR_o \simeq 10^{15}$ cm.

By assuming that the rising time of the main LC of SN 2006oz ($\simeq 30$ days) corresponds to the diffusion time t_d of the dense CSM, the electron density n_e in the dense CSM can be estimated from the following equation:

$$t_d \simeq \frac{\tau_T(R_o - xR_o)}{c}, \quad (1)$$

where $\tau_T = \sigma_T n_e (R_o - xR_o)$ is the Thomson scattering optical depth within the dense CSM, c is the speed of light, and σ_T is the Thomson scattering cross section. From Equation (1),

$$n_e \simeq \frac{ct_d}{\sigma_T(R_o - xR_o)^2} \simeq 5 \times 10^{10} \text{ cm}^{-3}. \quad (2)$$

The last value of Equation (2) is estimated by adopting the parameters for SN 2006oz, i.e., $t_d = 30$ days, $xR_o =$

TABLE 1
MODEL PARAMETERS OF SN 2006oz

R_i cm	xR_o cm	R_o cm	n_e cm^{-3}	CSM Density g cm^{-3}	CSM Mass M_\odot
10^{15}	10^{15}	2.5×10^{15}	5×10^{10}	10^{-12}	35

10^{15} cm, and $R_o = 2.5 \times 10^{15}$ cm. $\tau_T = 52$ in this case and it is plausible that the shock breakout occurs in the CSM with the typical forward shock velocity $v_s \simeq 10,000 \text{ km s}^{-1}$ ($c/v_s \simeq 30$).

If the dense CSM is composed of 50 % C and 50 % O and both C and O are singly ionized in the entire CSM, the CSM density corresponding to $n_e \simeq 5 \times 10^{10} \text{ cm}^{-3}$ is $\rho_{\text{CSM}} \simeq 10^{-12} \text{ g cm}^{-3}$. Then, the required CSM mass is $\simeq 35 M_\odot$. If we further assume that the outflowing velocity of the dense CSM was 100 km s^{-1} , the $35 M_\odot$ of C+O-rich materials must have been lost from the progenitor within 8 years before the explosion at a rate of $\simeq 7 M_\odot \text{ yr}^{-1}$. Mechanisms by which WR stars experience such a huge mass loss just before the explosion have not yet been clarified, although there are some suggestions (e.g., Quataert & Shiode 2012). Alternatively, the dense CSM does not necessarily need to come from the huge mass ejection from the progenitor. Within a dense cluster, collisions of WR stars may leave dense C+O-rich envelopes that would persist until the time of the explosion. This is an alternative way to have a dense C+O-rich CSM around an SN (see also, e.g., Portegies Zwart & van den Heuvel 2007; Pan et al. 2012; Chevalier 2012).

3. A DIP AS A SIGNATURE OF THE SN-CSM INTERACTION

Based on the properties of the dense CSM required by the SN-CSM interaction scenario to power the main LC of SLSN 2006oz discussed above, we now investigate a consequence of this scenario in the early phase before the main LC. We suggest that there must be a brief phase of decreased luminosity lasting for a few days before the strong interaction energizes the main LC. This argument is independent of any assumptions regarding the nature of the early emission which will be discussed in Section 4. The only requirement is that there is a detectable, i.e., sufficiently luminous, early emission phase. The dip phase should then appear as the fading phase between the early emission and the main LC.

Figure 1 summarizes our model for the dip after the early emission. Before the explosion, most of C and O in the dense CSM is not ionized, and thus the CSM is transparent. This is because of the high CSM density which results in the high recombination rate ($\simeq 10^{-12} \text{ g cm}^{-3}$ estimated for SN 2006oz). The emission rate of the ionizing photons from a typical WR star ($10^6 L_\odot$ and 10^5 K) is $\sim 10^{49} \text{ s}^{-1}$. With the recombination coefficient $\sim 10^{-13} \text{ cm}^3 \text{ s}^{-1}$, the number of ionizing photons is too small to keep the dense CSM ionized.

Then, the central star explodes as an SN. Before the ejecta reaches R_i (Figure 1b), the SN ejecta expands within the rarefied region below R_i . We attribute the early emission in the LC to the light from the SN ejecta in this phase before the strong collision. The duration of the early emission in SN 2006oz before the main LC is about 10 days. Regardless of the nature of the early emission, the duration can be interpreted as the time re-

quired for the SN ejecta to reach the dense CSM (i.e., at R_i) in our scenario. With $v_s \simeq 10,000 \text{ km s}^{-1}$, it reaches $\simeq 10^{15} \text{ cm}$ in about 10 days and we can estimate that $R_i \simeq xR_o$. This is consistent with the estimated blackbody radius in this phase (Section 2).

Regardless of the mechanism to power the early emission, if the majority of photons emitted from the SN ejecta is in the optical or near-ultraviolet, most of C and O in the dense CSM will still not be ionized during the early emission phase. For instance, the blackbody radius and temperature of SN 2006oz during the early emission phase are $\simeq 10^{15} \text{ cm}$ and $15,000 \text{ K}$, respectively, and the emission rate of the ionizing photons ($\sim 10^{54} \text{ s}^{-1}$) is too small to keep most of the dense CSM ionized. Only the innermost thin layer of the dense CSM (up to $\simeq 1.2 \times 10^{15} \text{ cm}$) can be ionized in this case. The optical depth to the Thomson scattering in this ionized region becomes $\simeq 7$. However, the ionizing region is confined in the thin layer, and the diffusion time scale within it is estimated to be less than a day. Thus, the photosphere can be located in this thin layer of ionized material, but the effect on the LC evolution is expected to be small. Some recombination lines may be found in spectra at this phase. Nonetheless, most of the dense CSM is still transparent to optical photons, and thus we can observe the early emission.

After about 10 days after the explosion, the SN ejecta starts to collide with the dense CSM. Because of the strong interaction, X-rays and ultraviolet photons are now efficiently produced at the forward shock⁴, and the electron density in the dense CSM suddenly increases. The CSM gets ionized and the Thomson scattering makes the dense CSM opaque to any photons. Then, the diffusion velocity of photons can be less than the velocity of the shock wave, and photons cannot go out of the shock until the shock breakout takes place at xR_o (Figure 1c). During this optically thick phase before the shock breakout, the luminosity decreases. This sudden decline in the luminosity is a naturally-expected observable signature of the strong SN-CSM interaction scenario.

We suggest that the possible dip observed in SN 2006oz could be the first observed example of this signature. The duration of the dip in the LC of SN 2006oz was short. The luminosity at the single observed epoch after the early emission showed the decline, and the luminosity was back to the previous level by the next epoch (Leloudas et al. 2012, Figure 1). Therefore, the duration of the dip was at most 2 days. From this, we can place a constraint on the shock breakout: $xR_o - R_i$ should be less than $2 \times 10^{14} \text{ cm}$, or xR_o should be less than $1.2 \times 10^{15} \text{ cm}$, if $v_s = 10,000 \text{ km s}^{-1}$. We note that the duration of the dip can be very short, and thus high cadence observations are important to capture this signature.

After the shock breakout at xR_o , photons are able to escape out of the interaction region. Then, the SN luminosity is powered by the SN-CSM interaction, and the SN becomes super-luminous from the ongoing strong interaction (Figure 1d, Section 2).

4. DISCUSSION AND CONCLUSIONS

We suggest a new way to distinguish proposed power sources of SLSNe. Among scenarios proposed so far, the strong interaction scenario, which requires the existence of dense CSM, is distinguishable by the early phase LC before the rising part to the peak luminosity. The scenario predicts that a brief dip phase should appear before the main LC if there is an early emission which is bright enough to be observed, as was the case for the H-poor SLSN 2006oz. This argument is irrespective of detailed nature and origin of the early emission itself. The existence of the dip reflects the change in the ionization condition in the dense CSM following the SN-CSM interaction which results in the shock breakout within the CSM. The possible dip observed in H-poor SLSN 2006oz indicates that the main power source of the huge luminosity for this SLSN is the strong interaction between the SN ejecta and the dense C+O-rich CSM whose mass is estimated as $\simeq 35 M_\odot$. Other proposed power sources like magnetars may also happen to show a dip for a specific combination of model parameters and a dip may appear in some SLSNe but not in all SLSNe in these scenarios. On the other hand, a dip should always appear when the shock breakout occurs. Thus, more H-poor SLSN samples in the early phase are required to see whether a dip is a common feature of H-poor SLSNe and it is actually due to the shock breakout. We strongly encourage future observations in this direction.

The early emission of SN 2006oz itself is bright ($\sim 10^{43} \text{ erg s}^{-1}$), with the total radiation energy of $\sim 10^{49} \text{ erg}$ within $\simeq 10$ days. There are a few possible mechanisms to power the early emission. ^{56}Ni produced in the SN inside is one possibility. The color of the early emission obtained by Leloudas et al. (2012) is similar to that of Type Ia SNe near the LC peak (e.g., Wang et al. 2009). The required ^{56}Ni mass to explain the early emission luminosity is $\sim 1 M_\odot$. However, a difficulty in this model is that the rising time of the early emission is constrained to be at most 5 days (Leloudas et al. 2012), which is too short for the ^{56}Ni heating scenario. Another possibility is the interaction between the SN ejecta and CSM. It is possible that CSM which is less dense than the dense CSM above R_i exists below R_i . If there is additional CSM of $\sim 0.1 M_\odot$ below R_i , this is enough to create the luminosity of $\sim 10^{43} \text{ erg s}^{-1}$ through the SN-CSM interaction (Moriya et al. 2011). This small amount of CSM would not change the overall picture we suggest, since the total amount of the radiation energy emitted as the early emission ($\sim 10^{49} \text{ erg}$) is much smaller than the total available kinetic energy ($\sim 10^{51} \text{ erg}$ or even more) by the SN explosion and does not affect the dynamics of the shock wave so much.

The existence of $\sim 10 M_\odot$ C+O-rich CSM around a WR star which is lost just before its explosion clearly challenges the current understanding of stellar mass loss and stellar evolution. This drastic mass loss could influence the final progenitor mass at the time of its explosion and its fate. For example, stars which are currently considered to end up with a black hole due to fallback may actually become a neutron star because of the extra mass loss which reduces the mass of the accreting envelope material at the time of the core collapse. We still do not have a large number of observations to confirm that a WR star can actually have such mass loss and the dip is a common feature of H-poor SLSNe. Future observa-

⁴ As X-rays can reach inner orbit electrons, they may have difficulties to propagate outward.

tions of H-poor SLSNe especially in the early phases are essential for understanding the origin of H-poor SLSNe and the final fates of WR stars.

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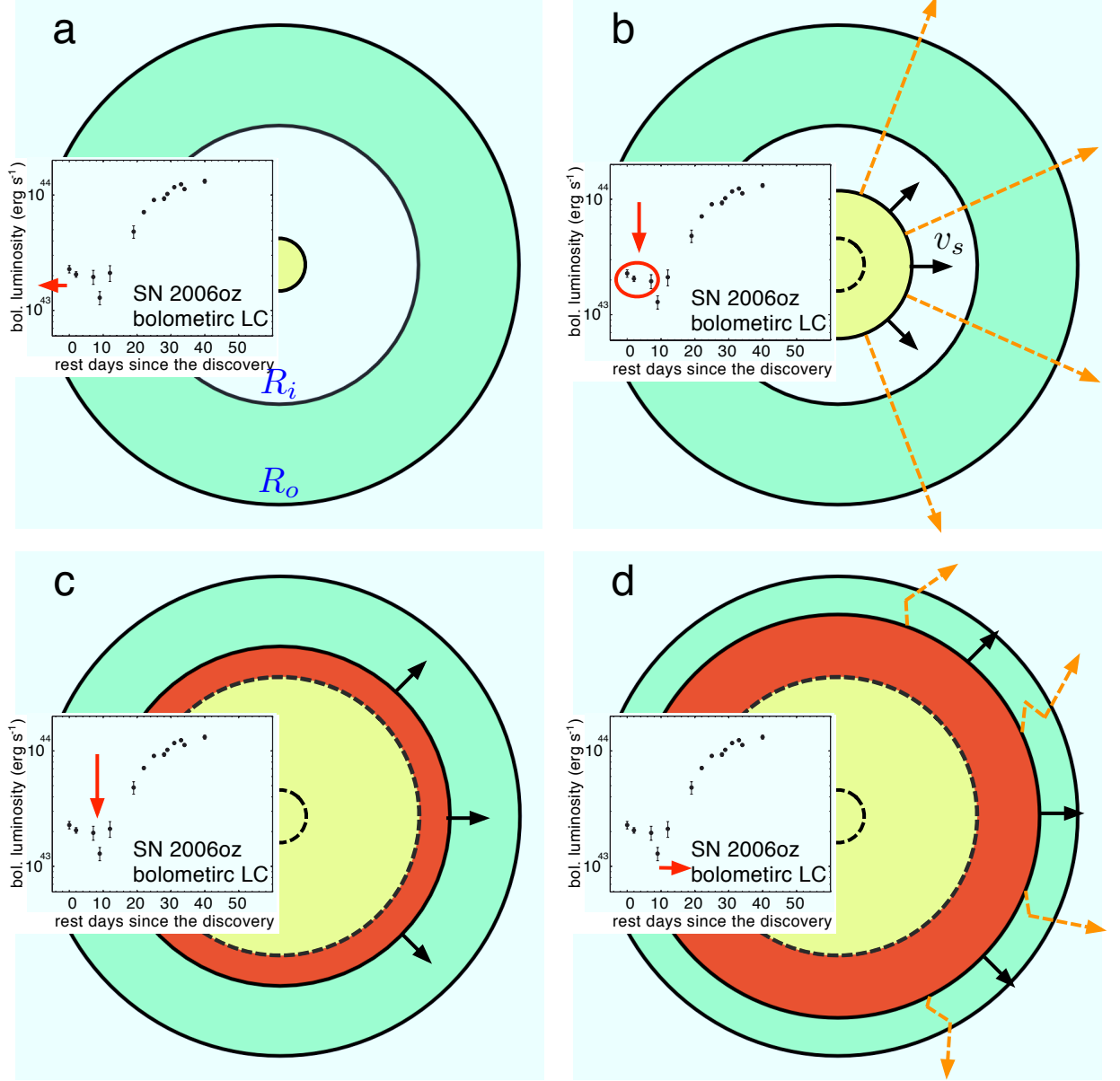


FIG. 1.— The proposed origin of the dip between the early emission and the main LC. The dense CSM, within which the shock breakout occurs, extends from R_i to R_o . A progenitor star explodes in this configuration (a). Before the forward shock reaches R_i (b), the dense CSM is transparent to optical photons from the SN ejecta and they can be observed as an early emission. When the forward shock reaches R_i (c), the opacity suddenly increases as ionization in the dense CSM is enhanced. Thus, even if the energy source of the early emission is still active, the dense CSM blocks the light, causing a dip in the LC. Then, after the shock breakout within the dense CSM (d), photons can escape from the shock. The SN is now powered by the strong interaction reaching the large luminosity in the main peak. The LC shown in each inset is the bolometric LC of SN 2006oz obtained by Leloudas et al. (2012).